Development of the MINERνA Detector

University of California-Irvine[†], Hampton University[§], Illinois Institute of Technology[†], James Madison University[§], Northern Illinois University[†], University of Pittsburgh[†], University of Rochester[*,†,§], Rutgers University[§], Tufts University[†],

The imminent completion of the NuMI beamline, which will be the highest intensity neutrino beamline in the world for many years after its completion, offers the particle and nuclear physics community a new opportunity. By constructing a fully active neutrino detector to run for the first time in a high rate neutrino beam, the MINERνA experiment, a collaboration between high energy physics and nuclear physics University and laboratory groups, proposes to exploit this opportunity to access a broad and rich program in neutrino scattering physics.

MINERνA will be able to complete a physics program of high rate studies of exclusive final states in neutrino scattering, of the connection between perturbative QCD and the non-perturbative regime, and of studies of the axial current in the elastic, DIS and off-forward regimes, as well as inside the nucleus. MINERνA then seeks the application of its data to aid present and future neutrino oscillation experiments, where understanding the details of neutrino cross-sections and final states is essential for separating backgrounds to oscillation from signal.

MINERνA can address all these topics, and can bring a new physics focus to the the community of users of frontier accelerators with a simple, low-risk detector of modest cost. The performance of this detector is expected to be excellent for resolving individual final states as well as measuring kinematics in inclusive reactions.

This proposed instrumentation development project under the NSF Major Research Instrumentation (MRI) program would fund fabrication of a stand-alone subset of the full detector by a consortium of University particle and nuclear physics groups. The proposed work includes completion of the MINERνA design and engineering, production of 40% of the active target volume including outer calorimeters, an electromagnetic calorimeter and an upstream veto, as well as construction of the read-out electronics and data acquisition.

When complete, this MRI fabrication project will allow operation of this subset of MINERνA upstream of the existing MINOS experiment magnetized iron-scintillator sampling near detector which can serve as a hadronic calorimeter and muon momentum analyzer. This subset of the detector can begin to explore the broad physics program of MINERνA with no additions, albeit with lower event rate and reconstruction efficiency. The MINERνA collaboration would seek to leverage the construction investment funded by this MRI by seeking additional funding to complete the full detector. If this MRI proposal is successful, the installation, utility and infrastructure costs for MINERνA would be borne by the host laboratory for the experiment, Fermi National Accelerator Laboratory (FNAL).

[*] Lead Institution on MRI Proposal

[§] Experimental Nuclear Physics

[†] Experimental Particle Physics

1 Research Activities

With this proposal, a subset of the MINERνA collaboration proposes to begin the fabrication of the MINERνA detector [1]. The MINERνA collaboration is a diverse group of nuclear and elementary particle physics experimentalists focused on the question of understanding neutrino-nucleus scattering in the few GeV regime. Naturally, this diverse group approaches these particle reactions seeking to answer a broad set of questions. How can we better understand neutrino interactions in order to measure neutrino oscillations? What can we learn about the structure of the nucleon and nucleus with a parity-violating probe? What can neutrino scattering teach us about the inner workings of the strong interaction in the non-perturbative regime?

The MINERνA collaboration currently consists of 44 physicists from 10 universities representing three countries and from two US national laboratories (FNAL and TJNAF). The groups represented primarily consist of senior personnel and a handful of postdocs during this proposal phase of the experiment; however, the University groups represented in this proposal have a collective record of training many graduate and undergraduate students in experiments in the FNAL and Kamiokande/KEK neutrino programs (Athens, Irvine, Pittsburgh, Rochester, Tufts) and the TJNAF Hall C program (Hampton, James Madison, Rutgers). Many of these groups have significant existing grants through the DOE High Energy Physics program and the NSF Nuclear Physics and Elementary Particle Physics programs which will allow them to support students and postdocs to explore the rich and broad physics program of MINERνA.

Once the MINERνA detector is complete, FNAL is committed in its schedules to currently run the NUMI beam through at least 2009, and other proposals for the more distant future are currently under active consideration by the lab. We therefore anticipate a long term physics program for the MINERνA detector.

1.1 Overview of the MINERνA Physics Program

Of the physics topics in the MINERνA program, several have not yet been studied in any systematic way, while others have only few results that are compromised by large statistical and systematic errors. A summary of these topics where MINERνA will break fresh ground include:

- Precision measurement of the quasi-elastic neutrino–nucleus cross-section, including its E_ν and q^2 dependence, and study of the nucleon axial form factors.

- Determination of single- and double-pion production cross-sections in the resonance production region for both neutral-current and charged-current interactions, including a study of isospin amplitudes, measurement of pion angular distributions, isolation of dominant form factors, and measurement of the effective axial-vector mass.

- Clarification of the W ($\equiv$ mass of the hadronic system) transition region wherein resonance production merges with neutrino deep-inelastic scattering, including tests of phenomenological characterizations of this transition such as quark/hadron duality.

- Precision measurement of coherent single-pion production cross-sections, with particular attention to target A dependence. Coherent π^0 production, especially via neutral-currents, is a significant background for next-generation neutrino oscillation experiments seeking to observe $\nu_\mu \to \nu_e$ oscillation.

- Examination of nuclear effects in neutrino-induced interactions including energy loss and final-state modifications in heavy nuclei. These nuclear effects play a significant role in neutrino oscillation experiments that measure ν_μ disappearence as a function of E_ν. With sufficient $\overline{\nu}$ running, a study of quark flavor-dependent nuclear effects will also be performed.

- Clarification of the role of nuclear effects as they influence the determination of $\sin^2\theta_W$ via measurement of the ratio of neutral-current to charged-current cross-sections off different nuclei.

- Much-improved measurement of the parton distribution functions will be possible using a measurement of all six ν and $\overline{\nu}$ structure functions (with sufficient $\overline{\nu}$ running).

- Examination of the leading exponential contributions of perturbative QCD.

- Precision measurement of exclusive strange-particle production channels near threshold, thereby improving knowledge of backgrounds in nucleon-decay searches, determination of V_{us}, and enabling searches for strangeness-changing neutral-currents and candidate pentaquark resonances. Measurement of hyperon-production cross-sections, including hyperon polarization, is feasible with exposure of MINERνA to $\overline{\nu}$ beams.

- Improved determination of the effective charm-quark mass (m_c) near threshold, and new measurements of V_{cd}, $s(x)$ and, independently, $\overline{s}(x)$.

- Studies of nuclear physics for which neutrino reactions provide information complementary to JLab studies in the same kinematic range.

In addition to being significant fields of study in their own right, improved knowledge of many of these topics is essential to minimizing systematic uncertainties in neutrino-oscillation experiments. Following is a sample of these topics that illustrate the potential of the MINERνA experiment:

1.1.1 Low-energy Neutrino Cross-sections

This is a topic of considerable importance to both present and proposed future (off-axis) neutrino oscillation experiments. With a total of over **2.8 million charged-current events** in the fiducial volume during a four-year run, MINERνA will be able to measure these cross-sections with negligible statistical errors and with the well-controlled beam systematic errors needed for the MINOS experiment

1.1.2 Quasi-elastic Scattering

Charged-current quasi-elastic reactions play a crucial role in both non-accelerator and accelerator neutrino oscillation studies. Cross-section uncertainties - often expressed as uncertainty in the value of the axial-vector mass - are a significant component in error budgets of these experiments. Currently available measurements of this cross-section are clustered below E_ν = 5 GeV with a few isolated measurements out to 12 GeV. The measurements have statistical errors of order (10-15)% plus another (10-20)% beam systematic error. MINERνA will measure the cross-section out to E_ν = 20 GeV with statistical errors ranging from $\leq$ 1% at low E_ν up to 7 % at E_ν = 20 GeV. The expected beam systematic error is (4-6) %.

There have been recent advances in the measurement of the vector component of elastic scattering from SLAC and Jefferson Lab. Measurement of the neutrino quasi-elastic channel is the most direct

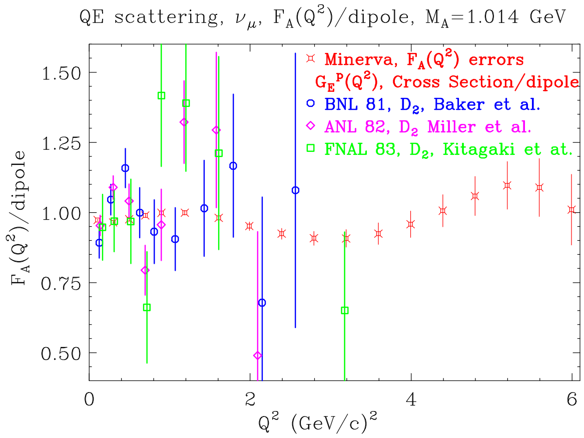

Figure 1: Extracted ratio F_A/F_A(Dipole) from the expected sample of quasi-elastic interactions from a four-year MINERνA run compared to the currently available measurements from early deuterium bubble chamber experiements [2], [3].

way to improve our knowledge of the axial-vector component to this channel. MINERνA's ability to carefully measure $d\sigma/dQ^2$ to high Q^2 allows investigation of the non-dipole component of the axial-vector form factor to an unprecedented accuracy. Figure 1 shows the extraction of the axial-vector form factor from the quasi-elastic event sample accumulated over a 4-year MINERνA run. The data points are plotted as a ratio of F_A/F_A(Dipole). Also shown are the currently available values of F_A from early experiments. MINERνA will be able to measure the axial nucleon form-factor with precision comparable to vector form-factor measurements at JLab.

Combining these MINERνA measurements with present and future Jefferson Lab data will permit precision extraction of all form factors needed to improve and test models of the nucleon. In addition, due to the well-constrained kinematics of this channel, a careful study of the muon and proton momentum vectors allows an important probe of nuclear effects.

1.1.3 Resonances and Transition to Deep-Inelastic Scattering

Neutrino Monte-Carlo programs, trying to simulate this kinematic region, have used early theoretical predictions by Rein and Sehgal[4] or results from electro-production experiments since existing data on neutrino resonance-production is insufficient for the task. It is noteworthy that the theoretical and experimental picture of the resonance and transition regions are far more obscure than the quasi-elastic and deep-inelastic scattering (DIS) regions which border it and that much of the relevant MINOS event sample falls inside these poorly-understood resonance and transition regions. These kinematic regions will be carefully examined by MINERνA.

1.1.4 Coherent Pion Production

Both charged- and neutral-current coherent production of pions result in a single forward-going pion with little energy transfer to the target nucleus. In the neutral-current case, the single forward-going π^0 can mimic an electron and be misinterpreted as a ν_e event. Existing cross-section measurements for this reaction are only accurate to $\sim 35\%$ and are only available for a limited number of target nuclei [5].

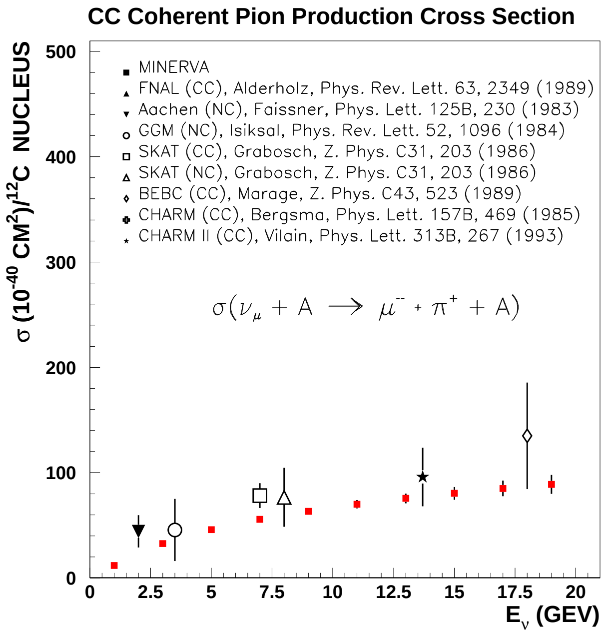

Figure 2: Coherent cross-sections as measured by MINERνA compared with existing published results. MINERνA errors here are statistical only.

Figure 2 shows the expected precision (statistical errors only) of the MINERνA measurement of the charged current coherent pion porduction cross-section as a function of neutrino energy. Here is is assumed that the measured value is that predicted by Rein-Seghal. Also plotted are the only currently available measurements showing their total errors

Another task for MINERνA will be comparison of reaction rates for lead, iron and carbon. The A dependence of the cross-section depends mainly on the model assumed for the hadron–nucleus interaction, and serves as a crucial test for that component of the predictions [6]. No experiment to date has been able to perform this comparison.

1.1.5 Nuclear Effects and their Impact on Neutrino Oscillation Studies

The study of nuclear effects with neutrinos involves the kinematics of the initial interaction (spectral function of the struck nucleon within the nucleus and Pauli-excluded interactions) and the evolution of the hadronic cascade as it proceeds through the nucleus. This has direct and important application to the MINOS neutrino oscillation experiment since, for a givien initial state neutrino energy, the final observed state may have a significantly lower visible energy [7, 8]. Since the determination of Δm^2 depends on knowledge of the initial E$_\nu$, understanding this energy distortion is crucial for a precise Δm^2 determination.

To quantify the effect this would have on a Δm^2 measurement, a toy monte carlo was used to approximate the MINOS Δm^2 analysis. Figure 3 shows the fractional size of the 90% confidence level contour region due to a 20% uncertainty in the total “neutrino hadronic energy loss”. Also shown in the figure is the size of the 90% CL region at $\sin^2 2\theta = 1$, versus Δm^2 ([9]). Although this systematic error would be smaller than the statistical error for the minimal exposure of protons on target, it is far from negligible, and dominates for values of Δm^2 below 1.5x10$^{-3}eV^2$ for all exposures.

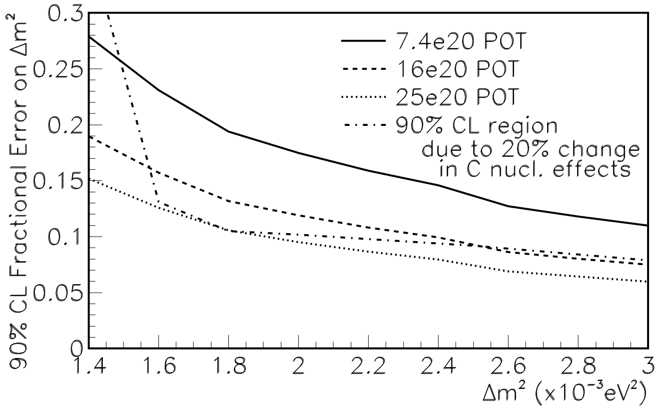

Figure 3: Fractional size of the 90% confidence level contour at $\sin^2 2\theta = 1$, due to MINOS statistical errors for different amounts of protons-on target (POT), and due to a 20% uncertainty on "neutrino hadron energy resolution" which would come about due to nuclear rescattering effects.

Without MINERνA the error due to nuclear effects may be roughly this size. The MINERνA experiment would permit a systematic, precision study of these effects by measuring multiplicities and total visible hadronic energy off a variety of heavy nuclear targets. With these results it should be possible to model this effect to much better than 10% of itself, making the uncertainty due to this effect negligible. In addition to MINOS, future Δm^2 measurements (such at those proposed at J-PARC or NuMI Off Axis), which expect to achieve a statistical precision roughly three times better than MINOS, will be even more dependent on MINERνA's study of these effects.

2 Description of the Research Instrumentation

3 Impact of Infrastructure Project

The MINERνA collaboration is in an excellent position to ensure broad impacts and educational opportunities associated with its construction and physics program. These impacts can be demonstrated by the collaborators' record in graduate training, their involvement in and commitment to undergraduate training in research, the key role of a historically black institution in MINERνA, and finally a dedicated education and public outreach (EPO) program proposed as part of this fabrication project.

Graduate student opportunities are part of the bread and butter of the MINERνA program. The sheer breadth of the physics program at MINERνA is a cornucopia of Ph.D. thesis topics, and the experiment is small enough in scale (at least by particle physics standards) that individual students can make a big impact on the experiment. Most of the collaborating Universities support significant numbers of graduate students in experimental nuclear and particle physics. One graduate student, Jesse Chvojka from Rochester, has already contributed significantly to the design of the MINERνA electromagnetic calorimeter and studies of π^0 reconstruction.

This commitment to student training in the research environment by MINERνA collaborators extends to undergraduates as well. The majority of our collaborating institutions (UC-Irvine, Hampton, James Madison, Rochester, Rutgers, and Tufts) plan to support undergraduates directly as part of this proposal. A number of our collaborating institutions have active NSF REU sites (Hampton, Pittsburgh, Rochester) and a history of training undergraduates in particle and nuclear physics research through these programs. Finally, we note that James Madison University is a non-Ph.D.-granting institution with access to an undergraduate student body that would not be exposed to research in particle and nuclear physics without opportunities like this program.

One of the largest contributors to this fabrication effort, Hampton University is an historically black institution. According to AIP statistics in 2001 [10], the HU Physics Department graduated over 70% of the African-American PhDs nationally. We note also that the first two nuclear physics PhDs ever awarded to African-American women from an HBCU graduated from Hampton in 2001 and 2002, respectively. Through Hampton's strong involvement, starting with a key construction role involving undergraduate and graduate students, this proposal will provide state-of-the-art training for young African American researchers. These opportunities address a national need for diversity in the educational pipeline and growth in programs that can attract African-American students into science to address the troubling fact that African-Americans currently make up less than 10% of the undergraduate science population, under 5% of the graduate population, and less than 2% of the doctoral majors nationally [11].

Finally, to ensure the educational impact of MINERνA beyond the confines of the collaborating Universities and their students, we have proposed a program in EPO to complement the construction program. This program has two main facets: development of a public web page and event display link, and construction of a "mini-MINERνA" detector for use in secondary school visits and other outreach efforts of MINERνA collaborators. In addition, these projects will be completed primarily by teams of undergraduate students, secondary educators and their students with assistance from graduate students. A brief summary of the two EPO projects follows. The total budget requested for EPO activities, including the NSF portion of requested equipment costs and participant stipends and subsistance support is $55,745.

UC-Irvine and Tufts University will work to develop a public web page explaining the MINERνA experiment, how neutrinos interact and how we study them. Prof. David Casper at UC-Irvine, who will supervise this sub-project, has developed successful public web pages in the past recounting the discovery of neutrino oscillations [12]. Most of the work would be done by undergraduate summer students, supervised by Prof. Casper and Dr. Gallagher of Tufts, with consulting help from the public relations offices of UC-Irvine and Tufts University. In the second year of this two-year project, a graduate student from Irvine familiar with the DAQ would work to develop an online event display which would initially read from a library of simulated events, but would transition to live event displays from MINERνA as soon as the construction project is complete and the detector is active. In addition, funds for a modest web server to host this page are requested from the project.

In the second project, the University of Rochester will host a team of undergraduates, a secondary school teacher and students, and a graduate student for one summer to develop a small version of an extruded scintillator strip detector (mini-MINERνA) to demonstrate the detection of cosmic rays. To simplify the data acquisition, mini-MINERνA would not use the MINERνA MAPMTs and front-end electronics, but rather a multi-stage image intensifier connected to a network-attached camera for data acquisition. The secondary school teacher and students would be recruited from the base of teachers currently involved with the Rochester PARTICLE program [13], and initial use of the mini-MINERνA detector would focus on serving as a demonstration apparatus for classroom visits as part of PARTICLE. Equipment funds are requested for the image intensifier and camera, but other materials for the project as well as modest technician and machining support will be obtained from scrap materials and existing technical staff supported in the process of constructing MINERνA.

4 Project Management and Plans

Construction of the MINERνA detector will be supervised by the University of Rochester, which accepts oversight of the construction project as the lead institution on this proposal. Dr. Howard Budd, who has significant experience in the management of large scale construction of scintillator-based calorimeters, including the CDF plug upgrade calorimeter and the CMS Hadronic Calorimeter (HCAL), will serve as the project manager.

Each institutions' responsibilities are summarized in the Instrumentation Description (Section 2), and detailed further in the budget justifications.

Once completed, and subsequently installed, the data obtained by MINERνA will be shared by the entire MINERνA collaboration. In addition, the close proximity of the MINOS experiments' near sampling detector may make it desirable to provide MINERνA data to MINOS as well, and vice versa for events extending from the subset of the MINERνA detector supported by this MRI into the MINOS detector.

Operation and support of the completed MINERνA detector will be the responsibility of the MINERνA collaboration and the host lab, FNAL, where appropriate. Personnel to provide this maintenance and support as well as analyze the MINERνA data will come from operating grants of the collaborating institutions.

The MINERνA collaboration will continue to recruit interested collaborators from nuclear and particle physics as a way of expanding the detector construction program and the physics program of the experiment.

References

[1] D. Drakoulakos *et al.* [The MINERνA Collaboration], "Proposal to Perform a High-Statistics Neutrino Scattering Experiment Using a Fine-grained Detector in the NuMI beam", December 2003 [rev. January 2004]. Submitted to the FNAL PAC. `http://www.pas.rochester.edu/minerva/`.

[2] N. J. Baker *et al.*, Phys. Rev. **D23**, 2499 (1981).

[3] T. Kitagaki *et al.*, Phys. Rev. **D26**, 436 (1983).

[4] D. Rein and L. M. Sehgal, Annals Phys. **133**, 79 (1981).

[5] G. Zeller, To be published in *Proceedings of the Second Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NUINT02),* Irvine, California (2002).

[6] E. Paschos and A. Kartavtsev (private communication).

[7] M.K. Jones *et al.*, Phys. Rev. **C48**, 2800 (1993); R.D. Ransome *et al.*, Phys. Rev. **C46**, 273 (1992); R.D. Ransome *et al.*, Phys. Rev. **C45**, R509 (1992).

[8] D. Rowntree *et al.*, Phys. Rev. **C60**, 054610 (1999); B. Kotlinksi *et al.*, Eur. Phys. J. **A9**, 537 (2000).

[9] "Proposal for a Five Year Run Plan for MINOS", The MINOS Collaboration, NuMI-930, May 2003, submitted to the Fermilab Directorate, see `http://hep.caltech.edu/˜michael/minos/fiveyear.ps.`

[10] AIP Statistical Research Center, "Enrollement and Degree Report", AIP Pub. No. R-151.39

[11] National Science Foundation, Division of Science Resources Statistics, "Characteristics of Recent Science and Engineering Graduates: 2001", NSF 04-302, Project Officer, John Tsapogas (Arlington, VA 2003).

[12] `http://www.ps.uci.edu/˜superk/neutrino.html`

[13] `http://www.pas.rochester.edu/particle/`